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CAPACITANCE

(PREVIOUSLY RGP 083)

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1. INTRODUCTION.

1.1 The discovery of static electricity led to a number of important inventions amongst which were the Electroscope, the Wimshurst Machine, and the Leyden Jar.

Of these the Leyden Jar was the most important as it was the forerunner of the Capacitor which is so widely used in all electrical circuits.

Capacitors, which were formerly termed Condensers, are many and varied in sizes, type, and shape, and are necessities in all types of telecom circuits from telephone equipment to radio and television.

This paper deals with the basic construction, operation, and effects of capacitors in electric circuits.

2. THE ELECTRIC FIELD.

2.1 In previous papers it has been shown that when a P.D. is applied to a circuit in which a continuous current can flow, a magnetic field is set up which influences certain materials placed in its proximity.

Just as a current flow sets up a magnetic field composed of magnetic lines of force, so does a charge or voltage set up an electric field, considered to be composed of electric lines of force.

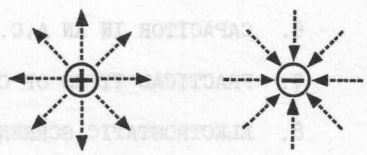
2.2 The electric field (or electrostatic field) is that space around a charged substance in which an electric force is apparent.

The insulating substance occupying the space of the electric field opposes the electric force set up by the charge, and is said to be electrically strained.

Electric fields and magnetic fields have many points in common.

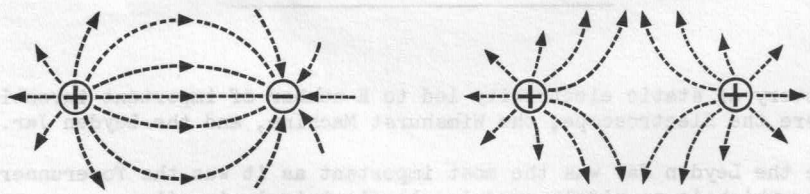
2.3 Lines of Force. We can imagine an electric force as due to "lines of electric force" or, simply, "lines of force". These lines radiate in all directions from an electric charge. We assume that the lines start from a positive charge (Fig. 1a) and end on a negative charge (Fig. 1b).

The attraction or repulsion between charged substances is due to the aiding or opposing of the lines of force. With unlike charges (Fig. 2a), the lines link up and tend to draw the substances together. With like charges (Fig. 2b), the lines are crowded and tend to push the substances apart.



(a) (b)

FIG. 1. LINES OF FORCE.



(b)

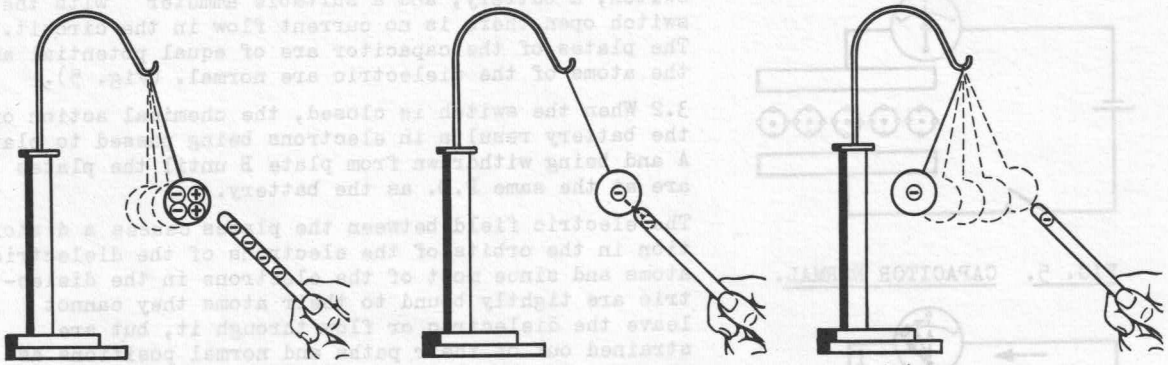
AIDING AND OPPOSING OF LINES OF FORCE.

FIG. 2.

Remember: This idea of lines of force is simply a convenient assumption to help us understand the behaviour of electrically charged substances. Although diagrams of electric fields usually represent the lines of force in one plane, we must remember that the force of the electric field acts throughout the whole of the space surrounding the charged substance, and not just along these imaginary lines.

2.4 The air or any other insulating material occupying the space around a charged body is called the dielectric, the derivation of the word meaning that electrical influences can take place across or through it. It will be seen later that the dielectric plays a major part in the effects produced by an electric field.

2.5 Influences of the Electric Field. An experiment which shows the influence that an electric field has on objects within its proximity, is one in which a suspended neutrally charged pith ball is placed in proximity to a charged ebonite rod. The negatively charged rod will first attract the pith ball and then when contact has been made, will repel it.



(a) Electrostatic Induction and Attraction. (b) Transfer of Charge by Conduction. (c) Repulsion.

FIG. 3. INDUCING A PERMANENT CHARGE ON A PITH BALL.

Electrons on the pith ball are repelled by the rod's negative charge, so that the side of the pith ball nearest the charge becomes positively charged, as in Fig. 3a. As "unlike charges attract" the pith ball is attracted to the rod. The induction of the charge affects both the dielectric and the pith ball, and precedes the attraction which takes place.

When contact is made, electrons pass from the rod and the pith ball's positive ions become neutralised (Fig. 3b). When the rod and side of the ball are at the same negative potential the two bodies will repel one another, as "like charges repel". (Fig. 3c).

Experiments with a positively charged glass rod and pith ball produce the same result, showing the influence that an electric field has on objects within it.

2.6 Plotting the electric field. If a very high voltage is applied to two conducting plates and pieces of hard rubber filings are sprinkled on a piece of paper which is placed over the plates, when the paper is lightly tapped, the rubber filings will align themselves as shown in Fig. 4.

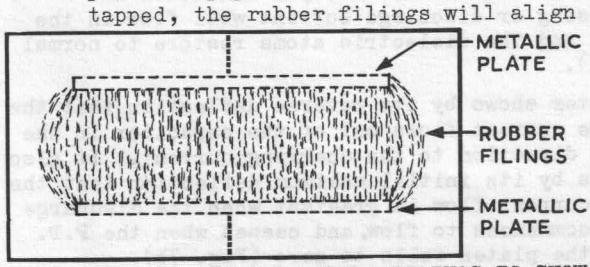


FIG. 4. USING HARD RUBBER FILINGS TO SHOW ELECTRIC FIELD.

The reason for this reaction is that the rubber filings provide a better conducting path for this field than does the air between the plates. The electric lines of force produced by the high voltage tend to follow the rubber particles and exert a force on them, so that they line up in the same way that iron filings line up when influenced by the magnetic lines of force from a magnetic field.

The shape of the electric field as shown in Fig. 4 indicates that the lines of force are not continuous as in a magnetic field but pass from the positively charged plate to the negatively charged plate.

The effects produced by electrostatic induction due to the electric lines of force from an electric field, have a similarity to magnetic induction produced by magnetic lines of force from a magnetic field, as in both cases the field affects certain objects within its influence, by induction.

3. THE CAPACITOR.

3.1 In its simplest form the capacitor consists of two conducting plates separated by a thin layer of air.

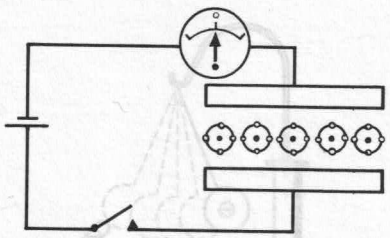
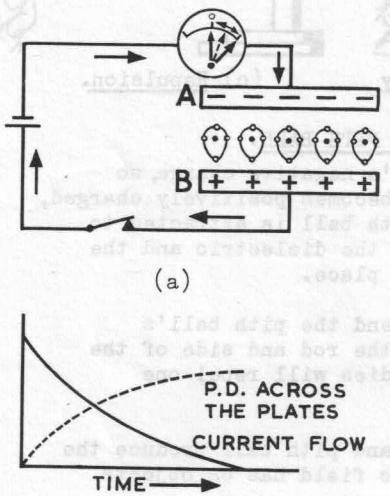


FIG. 5. CAPACITOR NORMAL.

When such a combination is connected in series with a switch, a battery, and a suitable ammeter with the switch open, there is no current flow in the circuit. The plates of the capacitor are of equal potential and the atoms of the dielectric are normal. (Fig. 5).

3.2 When the switch is closed, the chemical action of the battery results in electrons being passed to plate A and being withdrawn from plate B until the plates are at the same P.D. as the battery.

The electric field between the plates causes a distortion in the orbits of the electrons of the dielectric atoms and since most of the electrons in the dielectric are tightly bound to their atoms they cannot leave the dielectric or flow through it, but are strained out of their paths and normal positions as shown in Fig. 6a. In this condition the dielectric exhibits surface charges and is said to be "polarised".



(a)

(b)

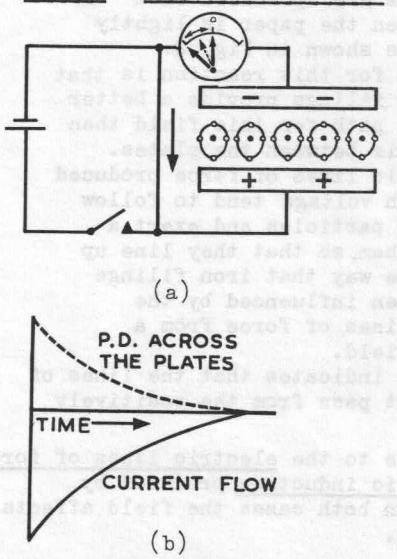
FIG. 6. CAPACITOR CHARGING.

The limited electron movement in the dielectric is commonly called a displacement current which is not an actual flow of electrons as in the case of a conductor, but is a small displacement due to the surrounding electrical forces.

There is an instantaneous deflection of the ammeter to a maximum value, which restores to normal as the current flow into the capacitor raises an opposing P.D. across the plates. Fig. 6b indicates that the current ceases to flow when the plate P.D. equals oppositely the applied voltage.

It should be noted that the rate of current flow into the capacitor is at its maximum when the P.D. across the plates is at a minimum. The rate of current falls as the P.D. across the plates is raised, and ceases when the capacitor is fully charged.

3.3 When the switch is opened the charge remains, but if the plates are connected by a conductor a neutralising or discharge current will flow in the circuit, and the dielectric atoms restore to normal (Fig. 7a).



(a)

(b)

FIG. 7. CAPACITOR DISCHARGING.

The ammeter shows by its reverse deflection that the discharge current flows out of the capacitor in the opposite direction to the charging current. It also indicates by its initial maximum deflection that the rate of current flow is greatest when the discharge current commences to flow, and ceases when the P.D. between the plates falls to zero (Fig. 7b).

3.4 From this it can be said that -

(i) A capacitor can be charged.
(ii) The charge causes a displacement of electrons within the insulating dielectric material resulting in the dielectric surfaces being "polarised".
(iii) The charge will remain when the energising source is disconnected.
(iv) The stored charge will flow out of the capacitor when a circuit is provided and the dielectric will restore to normal.

4. THE UNIT OF CAPACITANCE.

4.1 Capacitance is defined as the ratio of the charge of a capacitor to the P.D. between its plates. The unit of capacitance is a Farad. A capacitor is said to possess a capacitance of one farad when a charge of one coulomb raises the potential difference between the plates by one volt.

A farad may also be expressed as being the capacitance of a capacitor in which an applied e.m.f. of 1 volt will store one coulomb of electricity.

This can be expressed in the simple formula –

$$E = \frac{Q}{C}$$

where, E = P.D. in volts.
Q = charge in coulombs.
C = capacity in farads.

4.2 A comparison of the effects produced in the following analogy will assist in the understanding of capacitance and its unit, the farad.

Two tanks of different sizes have a quantity of water poured into them. If the quantity is the same for each, the water in each tank will be at a different level as shown in Fig. 8. The large tank has a lower level or "head" of water than the smaller tank, for the same quantity of water.

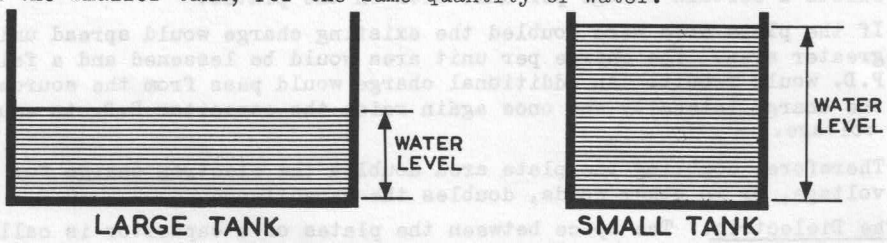


FIG. 8. THE SAME QUANTITY OF WATER PRODUCES DIFFERENT LEVELS OR HEADS OF WATER.

If the analogy is related to the charge that is passed into a capacitor, in comparison with the voltage that it produced across the plates, it will be understood that:-

When similar charges are passed into two capacitors of unequal capacitance the voltage produced across the larger capacitance will be less than that produced across the smaller capacitance.

It must also be understood that when similar voltages are applied across two unequal capacitances, a greater charge must flow into the larger capacitance in comparison to the smaller, before the P.D. across the plates is raised to the value of the applied voltage.

The farad is not an expression of the amount of charge that a capacitor can hold, but is the measure by which the voltage is raised when a certain charge passes into it.

4.3 Submultiple Units. A capacitor possessing a capacitance of one farad is too large both physically and electrically to be of practical use in electrical circuits.

Because of this, the following submultiple units are normally used –

(i) Microfarad (symbol μF, previously MF).
(ii) Micromicrofarad (symbol μμF, previously MMF) sometimes called picofarad (symbol pF).

The microfarad is equal to $\frac{1}{10^6}$ (10^{-6}) or one millionth of one farad.

The micromicrofarad is equal to $\frac{1}{10^{12}}$ (10^{-12}) or one million-millionth of one farad.

4.4 Conversion of submultiple units. Problems involving capacitors generally require the capacitance to be stated in terms of a farad.

To convert microfarads to farads, divide by 10^6.

To convert micromicrofarads to farads, divide by 10^{12}.

5. FACTORS AFFECTING CAPACITANCE.

5.1 The capacity of a capacitor is related to its constructional details and the whole can be expressed in the following statement.

The capacity of a capacitor varies directly as the cross-sectional area of the plates and the nature of the dielectric, and inversely as the distance between the plates.

$$C \propto \frac{AK}{d}$$

where,
C = capacity in farads.
A = area of the plates in contact with the dielectric.
K = dielectric constant.
d = distance between the plates.

5.2 Area of the Plates. The area of the plates in contact with the dielectric material determines the extent to which a charge can be spread over their surfaces.

When a capacitor is charged, the charging source causes transferred electrons to spread uniformly over one plate, making it negative, and electrons to be drawn from the other plate, making it positive.

These combined charges act on the dielectric, and the intensity of the charge on the plates determines the rise of P.D. across them.

Thus, when the capacitor is charged, and its P.D. equals the applied voltage, there exists a certain charge per unit area on the plates.

If the plate area were doubled the existing charge would spread uniformly over the greater area. The charge per unit area would be lessened and a fall of capacitor P.D. would result. An additional charge would pass from the source to maintain the charge intensity and once again raise the capacitor P.D. to equal the applied voltage.

Therefore, doubling the plate area doubles the electron charge for a given applied voltage, or in other words, doubles the capacitance.

5.3 The Dielectric. The space between the plates of a capacitor is called the dielectric, and may be occupied by air or any insulating material.

In relation to air, most materials pass electric lines of force more easily. This is shown by the example in paragraph 2.6 with the field between the plates of a capacitor traced out by hard rubber filings.

The dielectric material acts in much the same way as materials used in magnetic circuits, as the concentration of the field within it is dependent on the nature of the material used.

5.4 Dielectric Constant (Permittivity). The ratio between the lines of force produced in a dielectric by a given charge, to those produced when air (strictly vacuum) is used in its place is called that material's dielectric constant or permittivity, and is a measure of the extent to which the dielectric may be polarised.

For given plate sizes and spacings, the capacitance of a capacitor will increase in the direct ratio of the dielectric constant of the dielectric material used, to that of air as unity.

This means that when the air dielectric of a capacitor is replaced by mica, the capacity is increased about five times, and when replaced by dry paper the capacity is approximately doubled, for the dielectric constants of mica and paper are quoted as about 5.0 and 2.0 respectively in comparison to air (more correctly vacuous space) as unity.

5.5 Distance Between the Plates. When a capacitor is charged, and the plates are moved together, the effect of the electric field produces an increased attraction on the planetary electrons of the dielectric atoms, and increased polarisation of the surface of the dielectric occurs.

This increased surface polarisation reduces the effect of the charges on the plates which correspondingly reduces the P.D. between them.

If the capacitor is connected to a source of electricity a further charge will pass into the capacitor to raise the P.D. between the plates to that of the source.

When the plates are brought closer together the P.D. between them falls and the capacity increases.

When the plates are separated the P.D. between them rises and the capacity decreases.

5.6 Dielectric Strength. The limiting factor of the efficiency of a capacitor in preventing a current through it, is the insulating dielectric material. When the capacitor is charged, the field by induction strains the dielectric and causes displacement of electrons within it. The higher the charge, the higher the P.D. between the plates, and the greater the straining of the dielectric.

If an increase in charge raises the voltage above a critical value, the displacement of electrons within the dielectric will become a current flow from plate to plate, and the capacitor breaks down. The voltage at which breakdown occurs across a 1 mm. slab of the dielectric material is known as the material's dielectric strength.

For example, the dielectric strengths of air, mica and ebonite are given as about 4,300 volts, 60,000 volts and 50,000 volts respectively.

The maximum working voltage is usually indicated on the capacitor by the manufacturer. This value should never be exceeded.

6. CAPACITOR IN AN A.C. CIRCUIT.

6.1 Although experiments prove that a D.C. will charge a capacitor but will not pass through it, other experiments show that when a capacitor is included in an A.C. circuit, the effect produced in the circuit is as though the A.C. passes through the capacitor, to operate other components in the circuit.

For example, a generator, an ammeter, a suitable lamp, and a capacitor are connected in series as shown in Fig. 9.

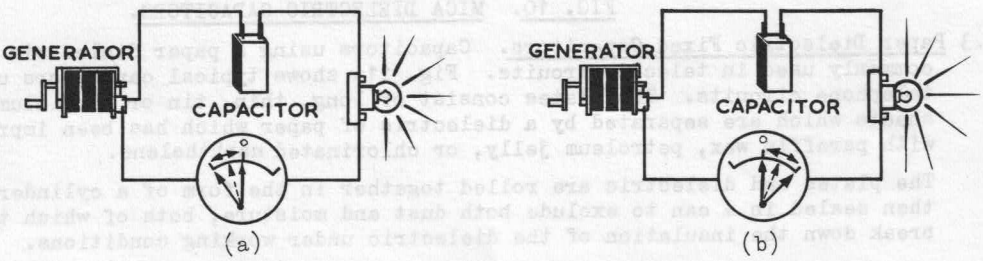


FIG. 9. CAPACITOR IN AN A.C. CIRCUIT.

When the generator is operated and the voltage rises to a maximum, the capacitor is charged, and when the voltage falls the capacitor discharges, to then be charged in the opposite direction by the next half cycle of A.C. which is of opposite polarity. When the voltage falls the capacitor will then discharge.

This continual charging and discharging takes place through the lamp and ammeter causing the lamp to glow and the ammeter to register the different directions of current. The current has the effect of passing through the capacitor, although it is only charged and discharged for each half cycle of current. (Figs. 9a & 9b).

This effect is used in telecommunication circuits, where a capacitor is connected in series with the bell in a telephone, to prevent a passage of D.C. through the bell, and yet allow the bell to operate when the alternating ringing potential is applied to the telephone from the exchange.

6.2 Capacitive Reactance:- We have seen how inductance offers an opposition, termed inductive reactance, to the flow of an A.C., which varies directly as the frequency of the current and the inductance of the circuit.

Similarly a capacitance offers an opposition to the flow of an A.C.

This is termed capacitive reactance which varies inversely as the frequency of the current and the capacitance of the circuit.

Capacitive reactance is expressed as follows:-

$$X_C = \frac{1}{2\pi f C}$$ where

X_C = capacitive reactance in ohms.
2π = 6.28
f = frequency in c/s.
C = capacitance in farads.

Later papers of the course will provide a fuller understanding of the effects and behaviour of capacitance, inductance and resistance in A.C. circuits.

7. PRACTICAL TYPES OF CAPACITORS.

7.1 Capacitors can be grouped into two classes - (i) Fixed Capacitors, (ii) Variable Capacitors.

Their symbols are:-

7.2 Mica Dielectric Fixed Capacitors. If a capacitor were made with two plates it would be large and cumbersome. To overcome this a number of small metallic plates are connected together. These are interleaved with another combination of small plates also joined together. A dielectric of mica is inserted between the plates. (Fig. 10b.) This gives the effect of a two plate capacitor in a small space (Fig. 10a). As mica possesses a high dielectric strength, a mica dielectric is generally used when a capacitor needs to withstand high voltages.

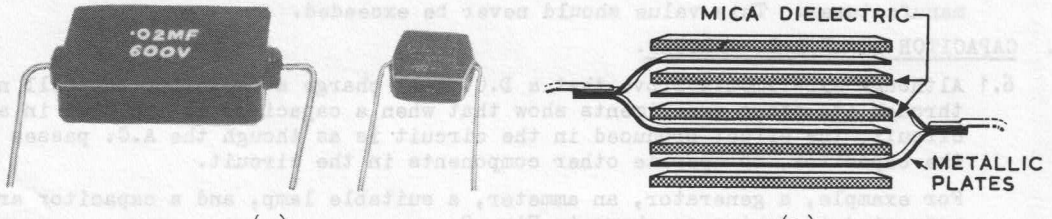


FIG. 10. MICA DIELECTRIC CAPACITORS.

7.3 Paper Dielectric Fixed Capacitors. Capacitors using a paper dielectric are commonly used in telecom circuits. Fig. 11a shows typical capacitors used in telephone circuits. The plates consist of long, thin, tin or aluminium foil sheets which are separated by a dielectric of paper which has been impregnated with paraffin wax, petroleum jelly, or chlorinated naphthalene.

The plates and dielectric are rolled together in the form of a cylinder which is then sealed in a can to exclude both dust and moisture, both of which tend to break down the insulation of the dielectric under working conditions.

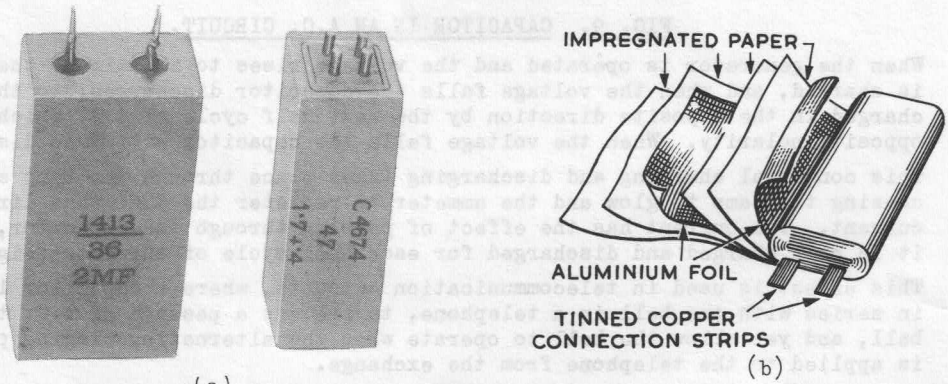


FIG. 11. PAPER DIELECTRIC CAPACITORS.

7.4 Electrolytic Fixed Capacitors. This type of capacitor depends for its action on the principle that two suitable electrodes in an electrolyte will allow a current to pass in one direction, but very little current in the opposite direction. In construction these capacitors may be of either the "Wet" or "Dry" types.

(i) Wet Electrolytic Capacitors. In its simplest form this type of capacitor consists of two aluminium plates which are in contact with an electrolyte of boric acid. The electrolytic action of a current which is passed between the plates through the electrolyte, during manufacture, forms a thin oxide on the surface of the positively connected plate. This insulating oxide acts as the dielectric of a capacitor and permits little or no current to pass when the capacitor is connected in circuit in the same polarity.

Since the dielectric is maintained by electrolytic action the electrolyte must have contact with the negative side of the voltage source, and the oxide coated plate must be connected to the positive source.

(ii) "Dry" Electrolytic Capacitors. The electrolyte used in this type of capacitor is not "dry" in the strict sense, but is a thick viscous substance held in some absorbing material such as paper or cloth.

The plates are generally of annealed aluminium foil separated by the electrolyte impregnated paper or cloth, the whole being rolled together in a compact roll which is inserted in a container and sealed (Fig. 12). The plate with the oxide coating is the positively connected terminal, and the other negative.

Unless of special design electrolytic capacitors can only be used in circuits where there are unidirectional currents, as a reverse polarity could break down the dielectric, and damage or ruin the capacitor.

In electrolytic capacitors the dielectric of oxide coating is less efficient as an insulator than mica or paper, and small leakage currents must be tolerated; also the coating and electrolyte deteriorate after a period of service. However, the advantages of large capacitance for a small space, and economy of cost, cause these capacitors to be widely used.

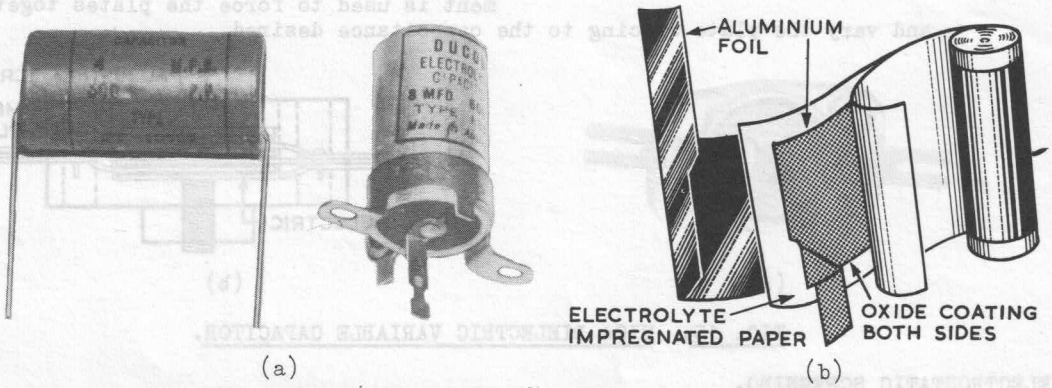


FIG. 12. TYPICAL "DRY" ELECTROLYTIC CAPACITORS.

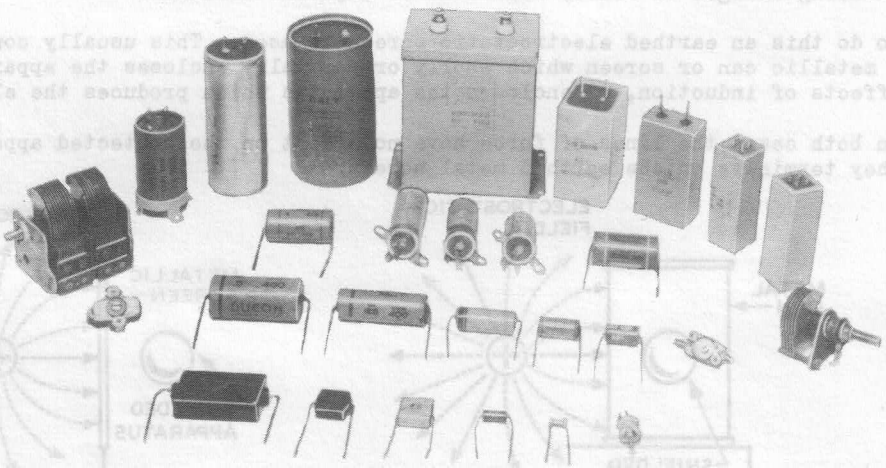


FIG. 13. TYPES OF CAPACITORS USED IN TELECOM.

7.5 Variable Capacitors.

(i) Air Dielectric Variable Capacitors (Fig. 14). The most common type employs a number of fixed and moving vanes or plates, usually made of brass or aluminium. These mesh with one another according to the capacitance required, and are separated by an air dielectric.

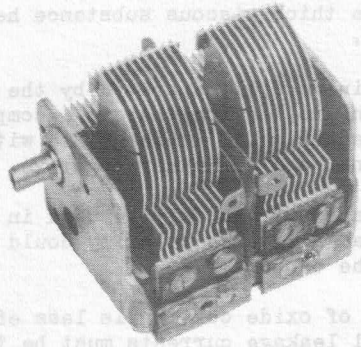
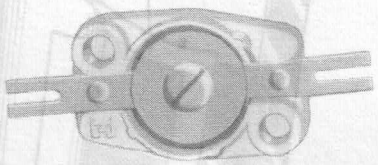


FIG. 14. AIR DIELECTRIC VARIABLE CAPACITOR.

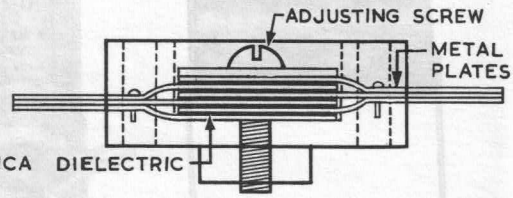
When the rotary plates are fully meshed between the stationary plates, the capacitance is at its maximum as the plate area is then at its greatest. As the movable plates are withdrawn from mesh the capacitance decreases.

The number of plates in combination determines the capacitance required, and common values in use range from 25 to 1000 μμF.

(ii) Mica Dielectric Variable Capacitor. (Fig. 15). This capacitor usually has a maximum value of less than 50 μμF and consists of a number of metallic plates with sheets of mica between them. A screw adjustment is used to force the plates together and vary the plate spacing to the capacitance desired.



(a)



(b)

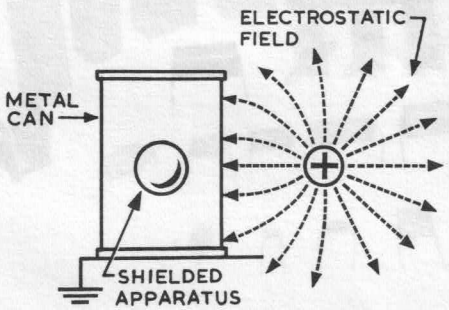
FIG. 15. MICA DIELECTRIC VARIABLE CAPACITOR.

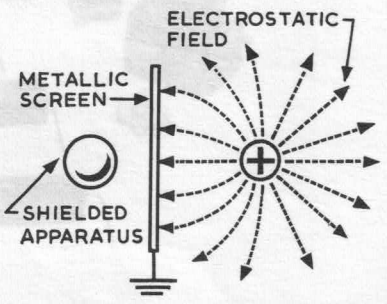
8. ELECTROSTATIC SCREENING.

8.1 In telecom circuits it is sometimes necessary to prevent an electric field from inducing charges on nearby apparatus or adjacent circuits.

To do this an earthed electrostatic screen is used. This usually consists of a metallic can or screen which wholly or partially encloses the apparatus from the effects of induction, or encloses the apparatus which produces the electric field.

In both cases the lines of force have no effect on the protected apparatus for they terminate on the earthed metal screen.





(a) Field terminates on earthed can. (b) Field terminates on earthed screen.

FIG. 16. FORMS OF ELECTROSTATIC SCREENING.

9. CAPACITORS IN SERIES AND PARALLEL.

9.1 When capacitors are connected in series or parallel the method of finding the total capacitance is opposite to that used in finding the total resistance of series or parallel resistors. Just as conductances represent the ease with which current flows, so does capacitance represent the ease with which electric flux is established.

Fig. 17 shows that connecting capacitors in series effectively increases the dielectric space, which decreases the total capacity to less than the smallest capacity in the combination.

When capacitors are connected in parallel, the effect produced is of one large capacitor with a plate area equal to the sum of the plate areas of the component capacitors. (Fig. 18).

9.2 Capacitors in Series.

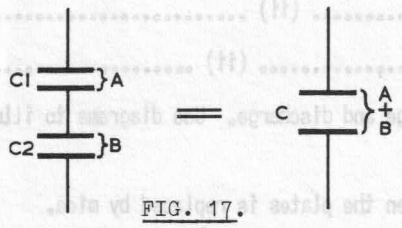


FIG. 17.

Thicker dielectric decreases capacitance.

Formula for Series Capacitors.

$$C = \frac{C1 \times C2}{C1 + C2}$$

or

$$C = \frac{1}{\frac{1}{C1} + \frac{1}{C2} + \frac{1}{C3}} \text{ etc.}$$

9.3 Capacitors in Parallel.

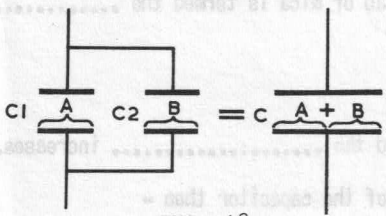


FIG. 18.

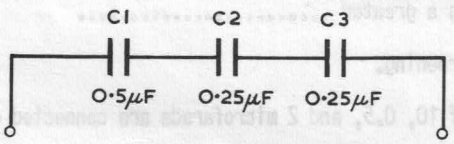
Larger plate area increases capacitance.

Formula for Parallel Capacitors.

$$C = C1 + C2 + C3 \text{ etc.}$$

In both cases C1, C2 and etc. must be expressed in similar units or subunits of capacitance.

9.4 Example (i). Calculate the total capacitance when three capacitors of 0.5 μF, 0.25 μF, and 0.25 μF, are connected in series.

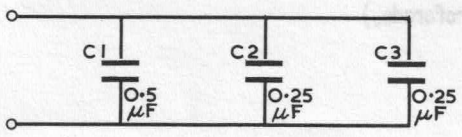


$$C = \frac{1}{\frac{1}{C1} + \frac{1}{C2} + \frac{1}{C3}}$$

$$C = \frac{1}{\frac{1}{0.5} + \frac{1}{0.25} + \frac{1}{0.25}}$$

Answer:- C = 0.1μF.

9.5 Example (ii). Calculate the total capacitance when three capacitors of 0.5 μF, 0.25 μF, and 0.25 μF, are connected in parallel.



$$C = C1 + C2 + C3$$

$$C = 0.5 + 0.25 + 0.25$$

Answer:- C = 1μF.

10. TEST QUESTIONS.

1. The electric field between charged bodies is considered to be composed of .....which pass from the ..... charged body to the ..... charged body.
2. The space or material surrounding a charged body is termed .....
3. Describe the effects produced when a positively charged body is placed in close proximity to a neutrally charged pith ball.
4. The unit by which capacitance is measured is called the .....
5. Explain the relationship between the charge passed into a capacitor in comparison with the P.D. produced across its plates.
6. The submultiple units of capacity are (i) ..... (ii) .....
7. Their relationships to the unit are respectively (i) ..... (ii) .....
8. Briefly describe the action of a simple capacitor during charge and discharge. Use diagrams to illustrate your answer.
9. What effect is produced in a capacitor if the air space between the plates is replaced by mica.
10. This effect is due to the ..... of mica.
11. The P.D. required to cause an electron flow through a 1 m.m. slab of mica is termed the ..... of mica.
12. Briefly explain what is meant by Capacitive Reactance.
13. Capacitive reactance decreases as the ..... and the ..... increases.
14. As the capacitance is dependent on the constructional features of the capacitor then -
    (i) The capacitance will ..... if the size of the plates is .....
    (ii) When the plates are moved apart, the capacitance .....
    (iii) The capacitance will ..... if the insulating material between the plates is changed for another material possessing a greater .....
15. Briefly explain what is meant by Electrostatic Screening.
16. Calculate the capacitance when three capacitors of 10, 0.5, and 2 microfarads are connected -
    (a) in series (0.385 microfarads)
    (b) in parallel (12.5 microfarads)
17. What is the capacitance when the 10 microfarads capacitor is placed in series with the paralleled 0.5 microfarads and 2 microfarads capacitors. (2 microfarads.)

END OF PAPER.